

# HERA results

H1, ZEUS and HERMES highlights

Helmholtz Program: Matter and the Universe

PoF III Topic: n.a. (PoF II Topic: HERA physics)

DESY Research Unit: Experimental Particle Physics

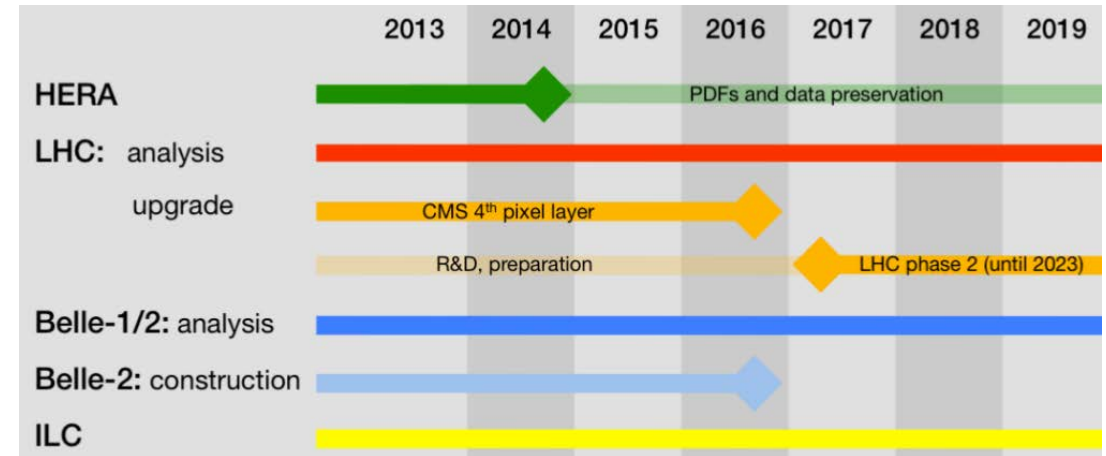
Stefan Schmitt

Center Evaluation DESY, 5 – 9 February 2018

# HERA in the PoF

- Data taking: 1992-2007
- HERA analysis: POF II (until 2014)
- No dedicated funding in POF III
- DESY scientists moved to other groups in 2014:  
ATLAS, CMS, Belle, ILC, ...
- HERA data preservation at DESY within the DPHEP initiative
- HERA collaborations ZEUS, H1, HERMES continue to produce scientific results
- Selected highlights of 2013-2017 are presented in this talk

DESY experimental particle physics  
(long-term plan shown in 2013)





# The HERA collider

Operation 1992-2007

## The HERA machine

- Polarized electrons or positrons at 27.6 GeV, protons at 920 GeV
- Centre-of-mass energy 320 GeV

## The experiments

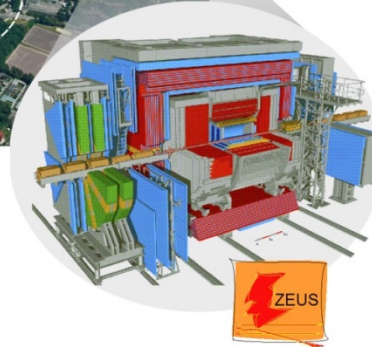
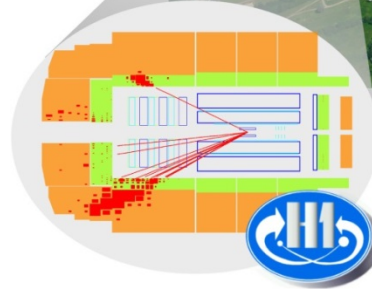
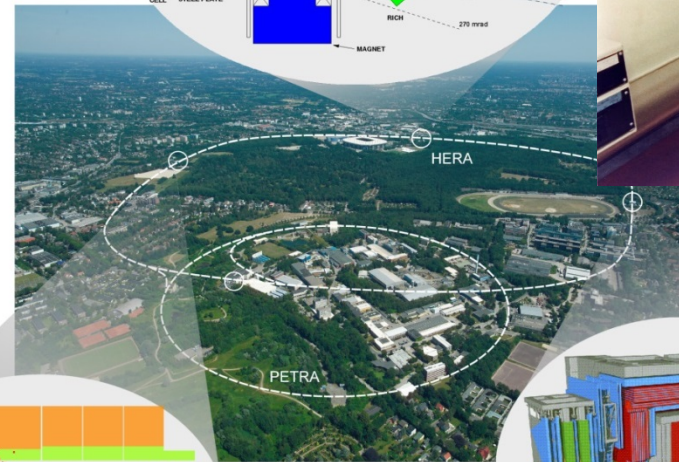
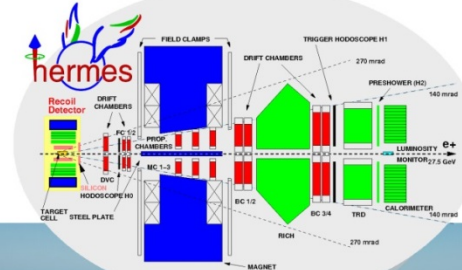
- Collider experiments H1 and ZEUS
- Lepton beam on polarized gas target: HERMES

## The data

- Total integrated luminosity H1+ZEUS:  $1 \text{ fb}^{-1}$
- Data are preserved for long-term analysis

## Scientific output (1992-2017)

- About 550 publications in peer-reviewed journals
- Thousands of talks on international conferences



# Selected recent results from HERA

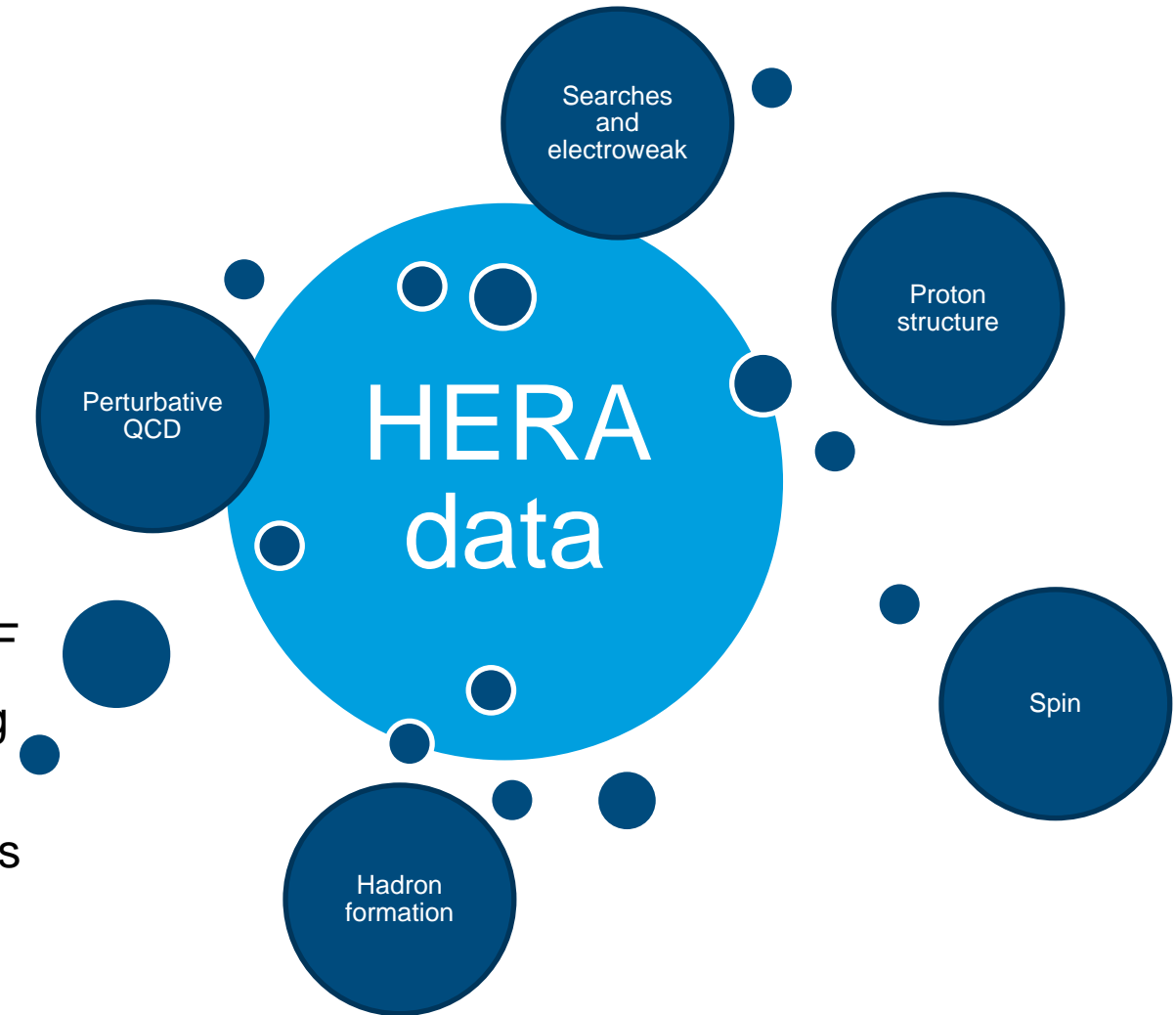
Highlight results achieved from 2013-2017

## Publications since 2013

- H1 and ZEUS combined: 2 papers
- H1: 12 papers
- ZEUS: 15 papers
- HERMES: 12 papers

## Selected results for this talk:

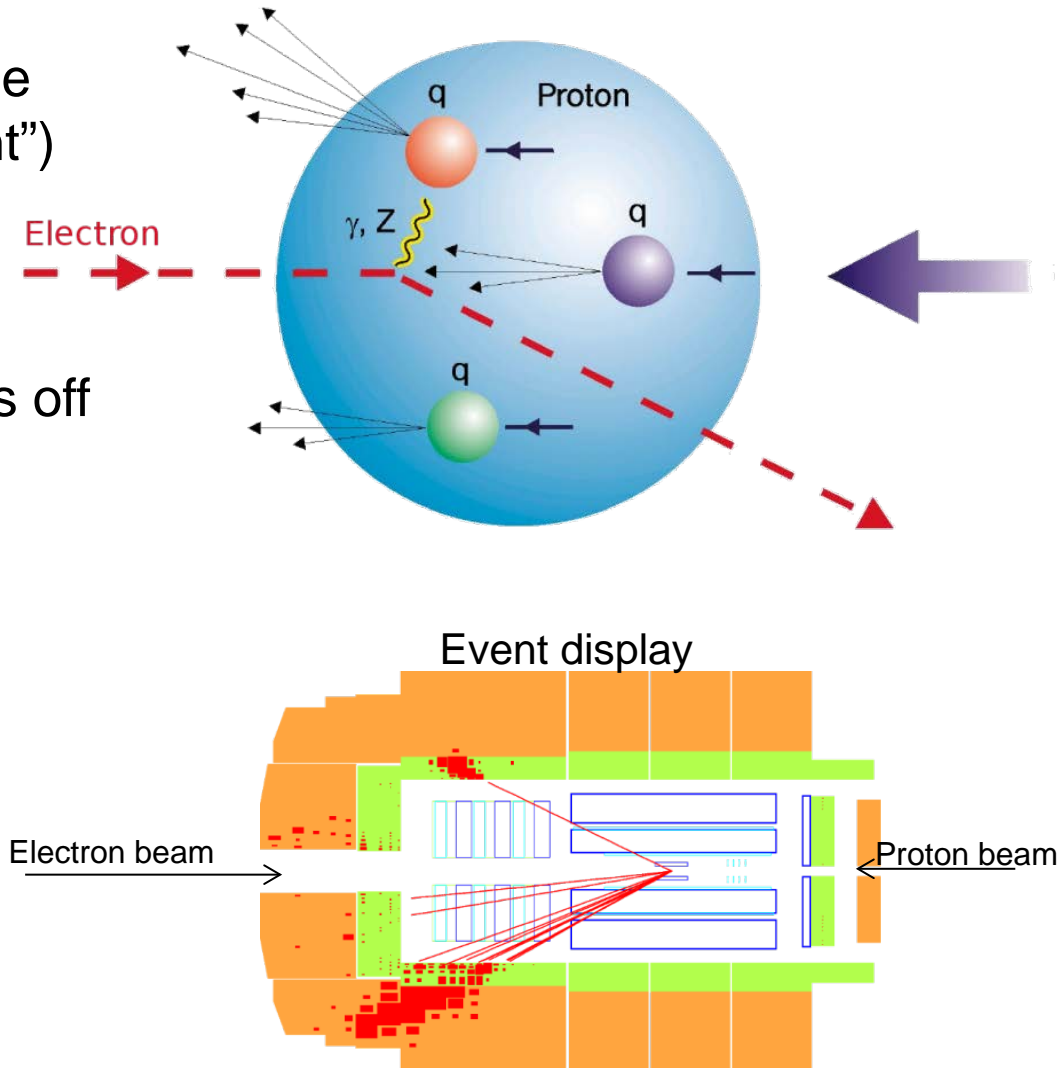
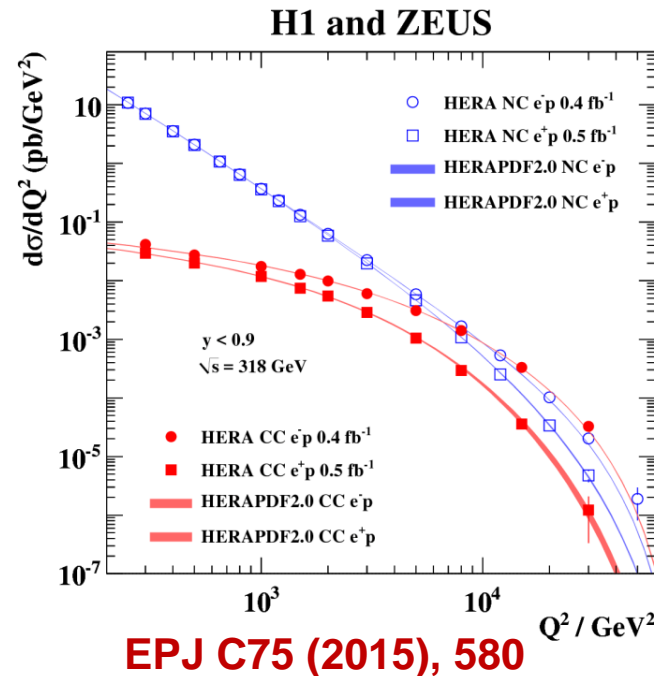
- **Searches and electroweak:** limit on the quark radius
- **Proton structure:** H1+ZEUS data combination and PDF
- **Perturbative QCD:** determination of the strong coupling at NNLO from jet data
- **Hadron formation:** HERMES identified pions and kaons
- **Spin:** HERMES identified pion and kaon production on transversely polarized target



# Deep-inelastic scattering (DIS)

at HERA

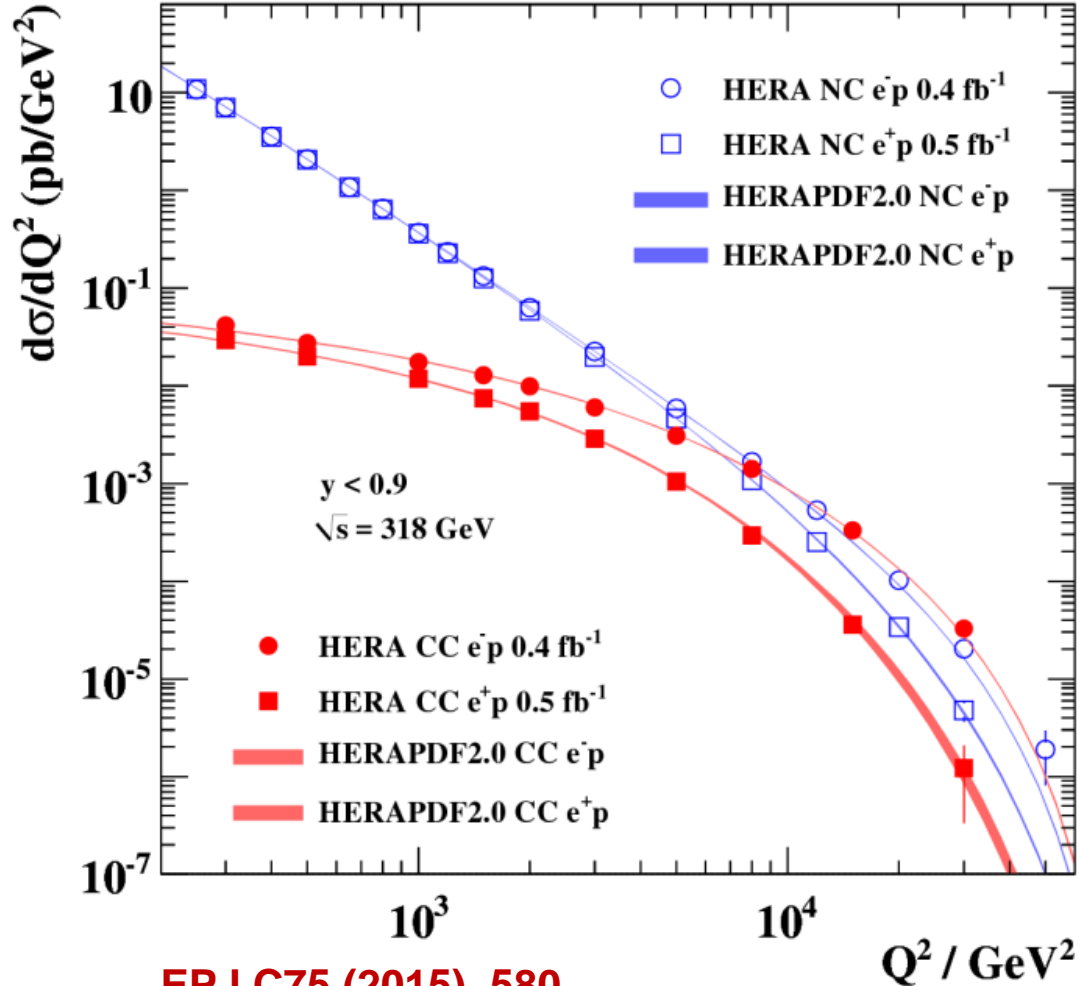
- Electrons interact with the protons by exchanging a gauge boson (photon or Z: “neutral current”, W: “charged current”)
- Momentum transfer:  $Q^2 = -(e-e')^2$
- Spatial resolution:  $R \sim 1/Q$
- Differential cross section or event rate per  $Q^2$  interval falls off steeply with increasing  $Q^2$
- Data are very precise (combination H1+ZEUS)
- At high  $Q^2$ , charged and neutral current cross section are similar in size
- Visualizes electroweak unification



# Limit on the quark radius from HERA data

HERA - the attometer microscope

## H1 and ZEUS

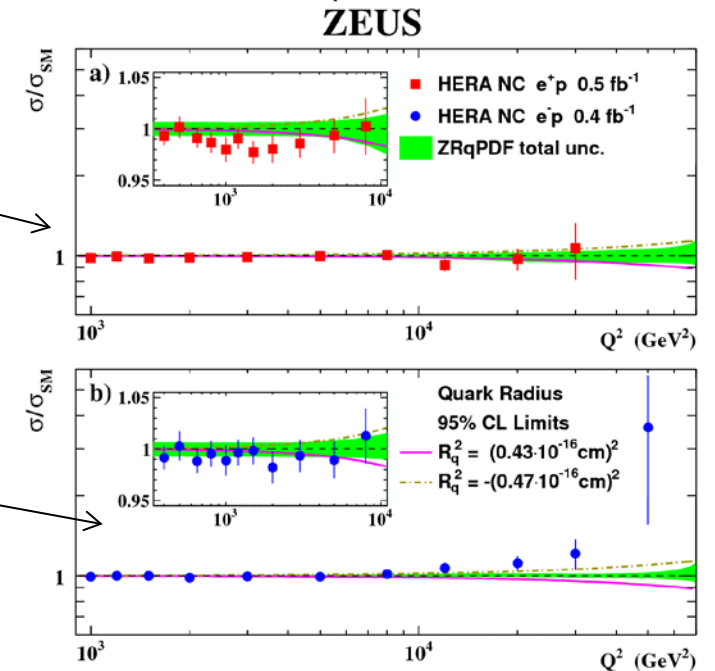


EPJ C75 (2015), 580

- Spatial resolution:  $R \sim 1/Q$
- HERA probes distances  $R < 10^{-18} \text{ m}$
- Electron is scattered on quarks in the proton
- Quarks are found to be point-like:  $R_q^2 < 0.43 \text{ am}^2$

Data are normalized to the prediction here

Compare to predictions with finite quark radius: set limit

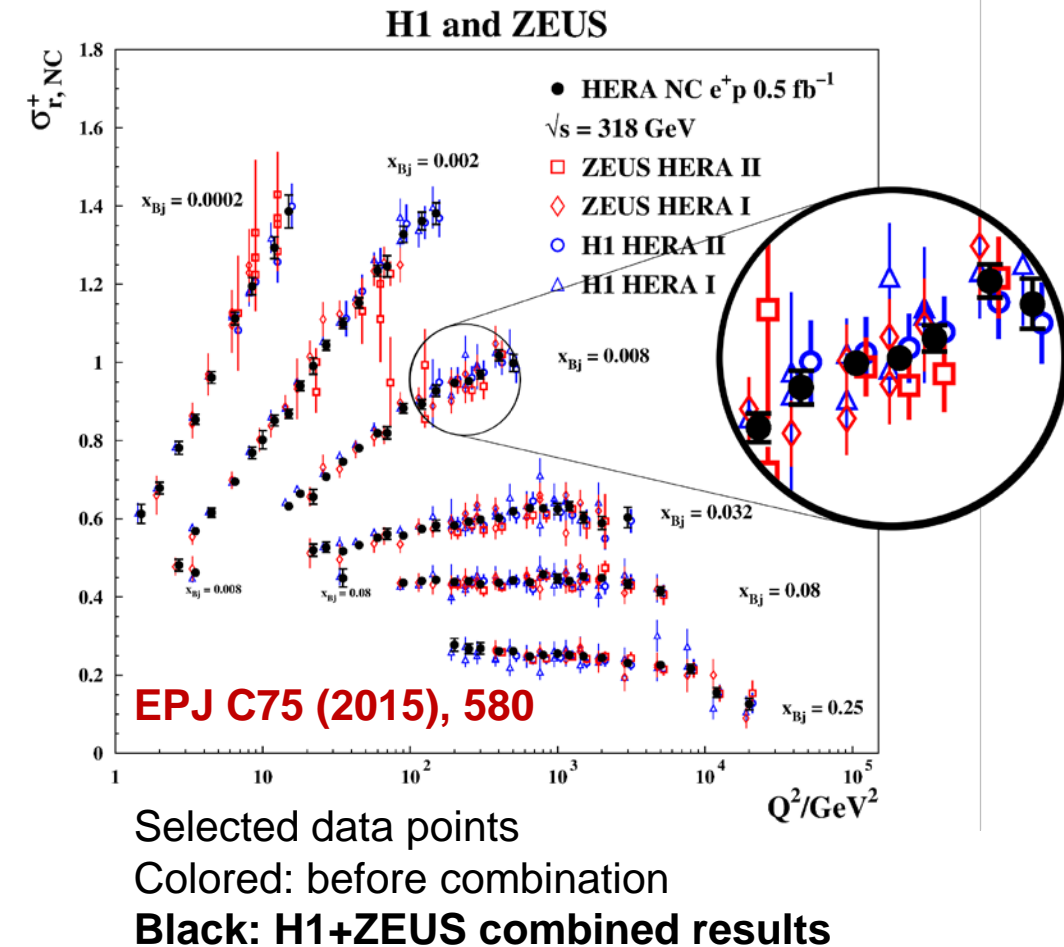


Phys.Lett.B757 (2016), 468

# H1 and ZEUS combined data

## Proton structure precision measurements

- **H1 and ZEUS data** on inclusive DIS and on charm/beauty production are **combined**
- **Goal:** reach best possible precision
- **Very high impact on the field**
  - 2009 combination of inclusive data: **~900 citations**
  - 2012 combination of charm data: **~200 citations**
  - 2015 combination of inclusive data: **~200 citations**
  - New publication on charm and beauty data combination in preparation
- **Data combination shown in this presentation:**
  - 2015 combination of inclusive data



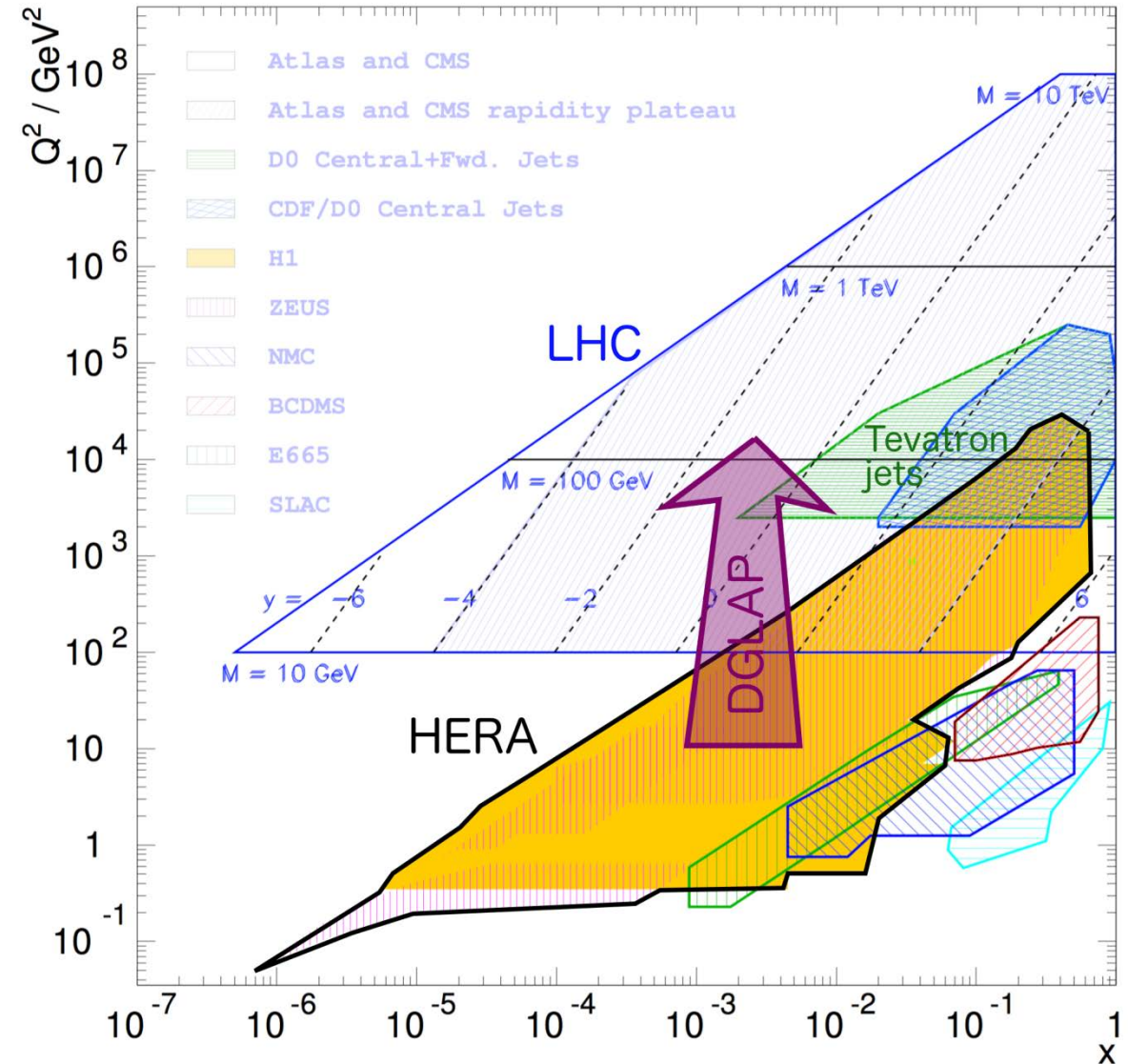
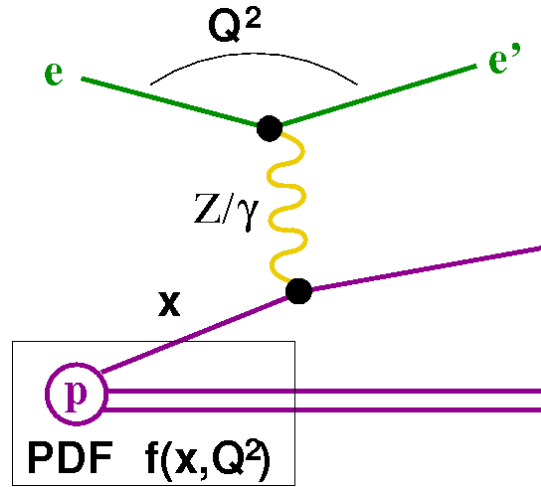
Shown here: reduced cross section as a function of  $Q^2$  and Bjorken- $x$   
( $x$  corresponds to the proton longitudinal momentum fraction taken by the struck quark)



# Inclusive HERA data: proton parton density functions (PDFs)

## The importance of HERA for LHC predictions

- DIS probes PDF most directly
- HERA data: reach to low  $x$  and large scales  $Q^2$
- DGLAP theory: connect PDFs at different scales
- Of greatest importance for LHC results: all their predictions depend on the PDFs (i.e. on the HERA data)

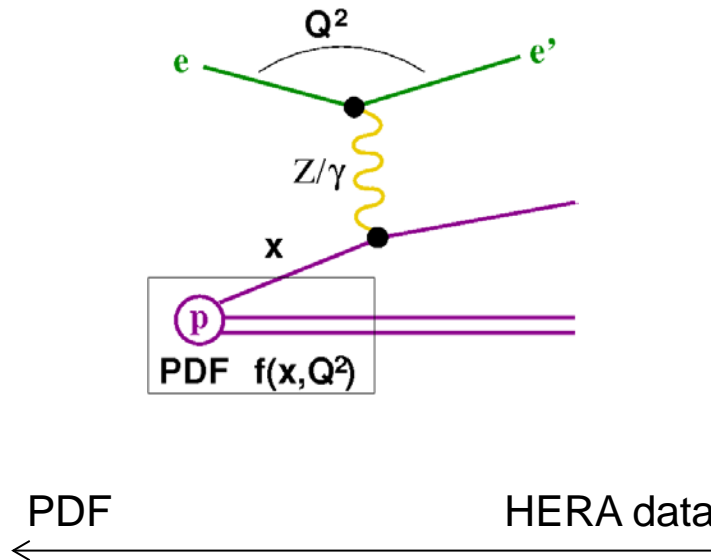
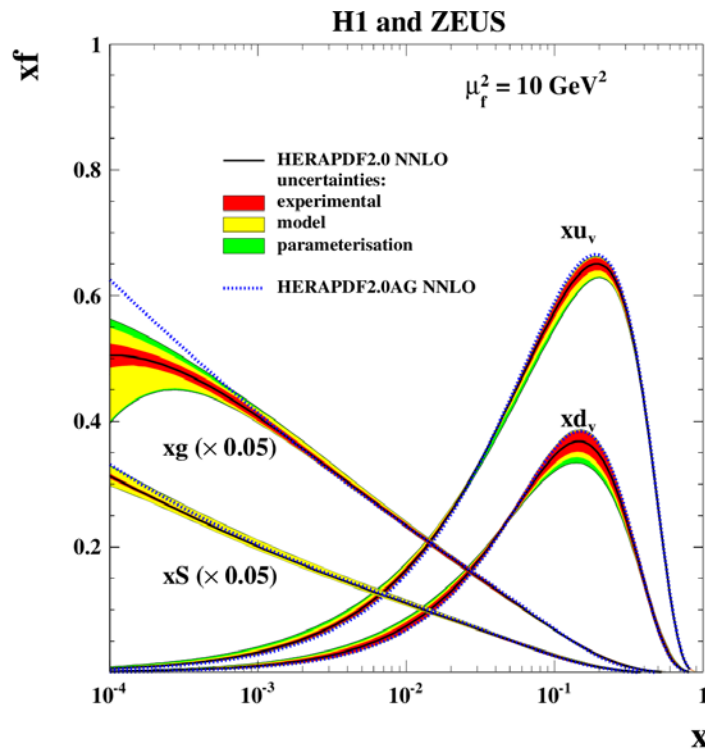




# PDF determination from HERA data

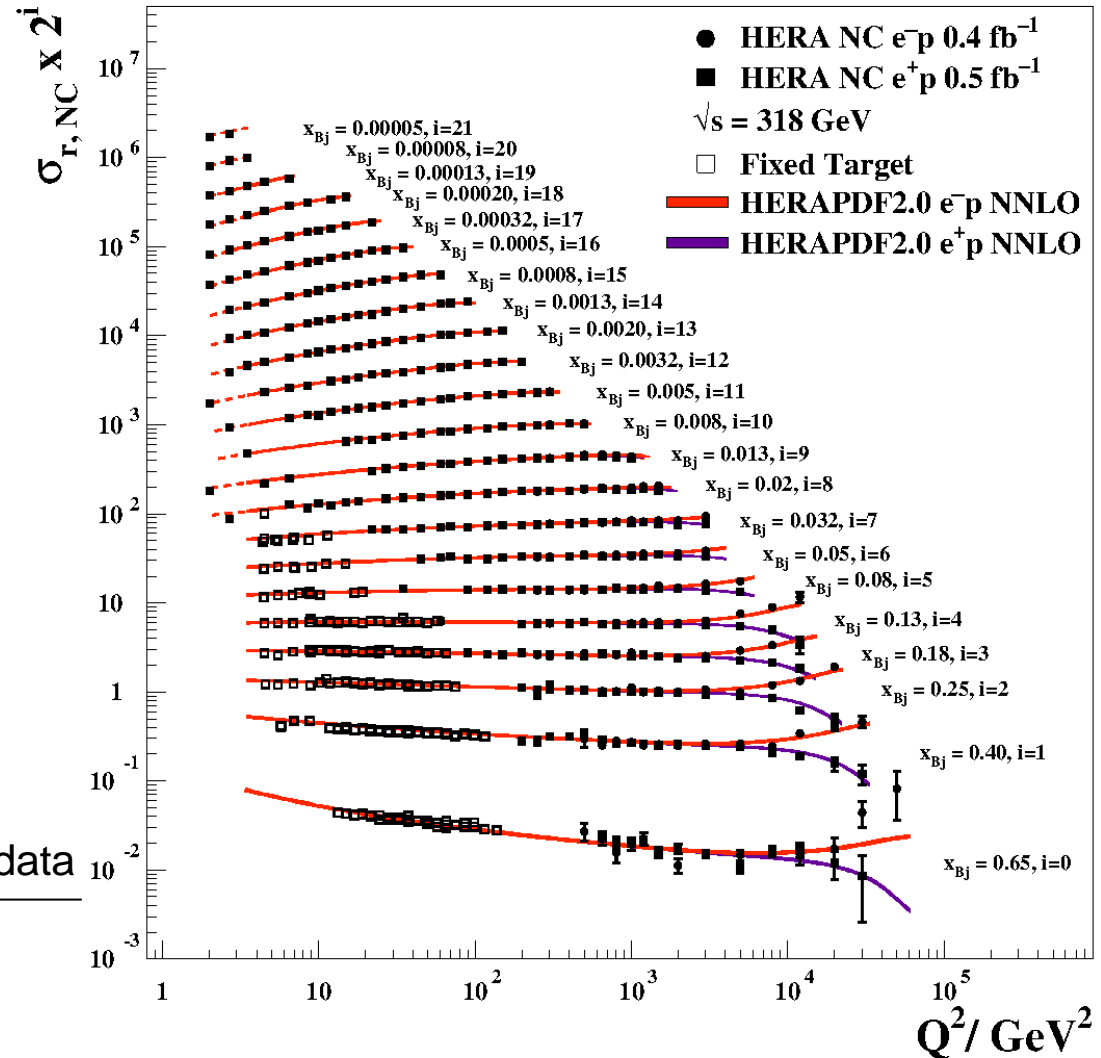
## Partons in the proton at small $x$

- High precision HERA data are used by all PDF fitting groups
- The paper got over 200 citations in only 2½ years
- HERAPDF2.0: determined from HERA data alone
- Main uncertainties: model and parametrisation variations



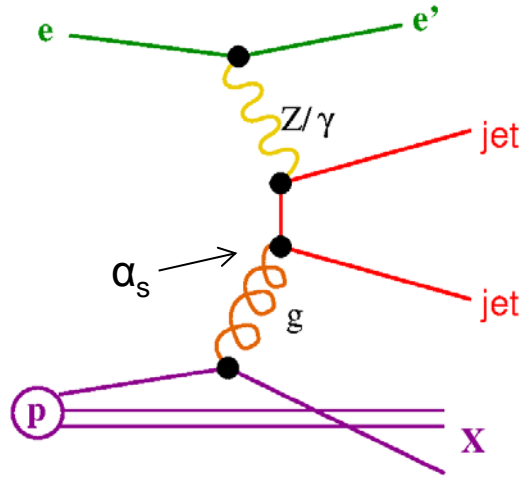
EPJ C75 (2015), 580

## H1 and ZEUS



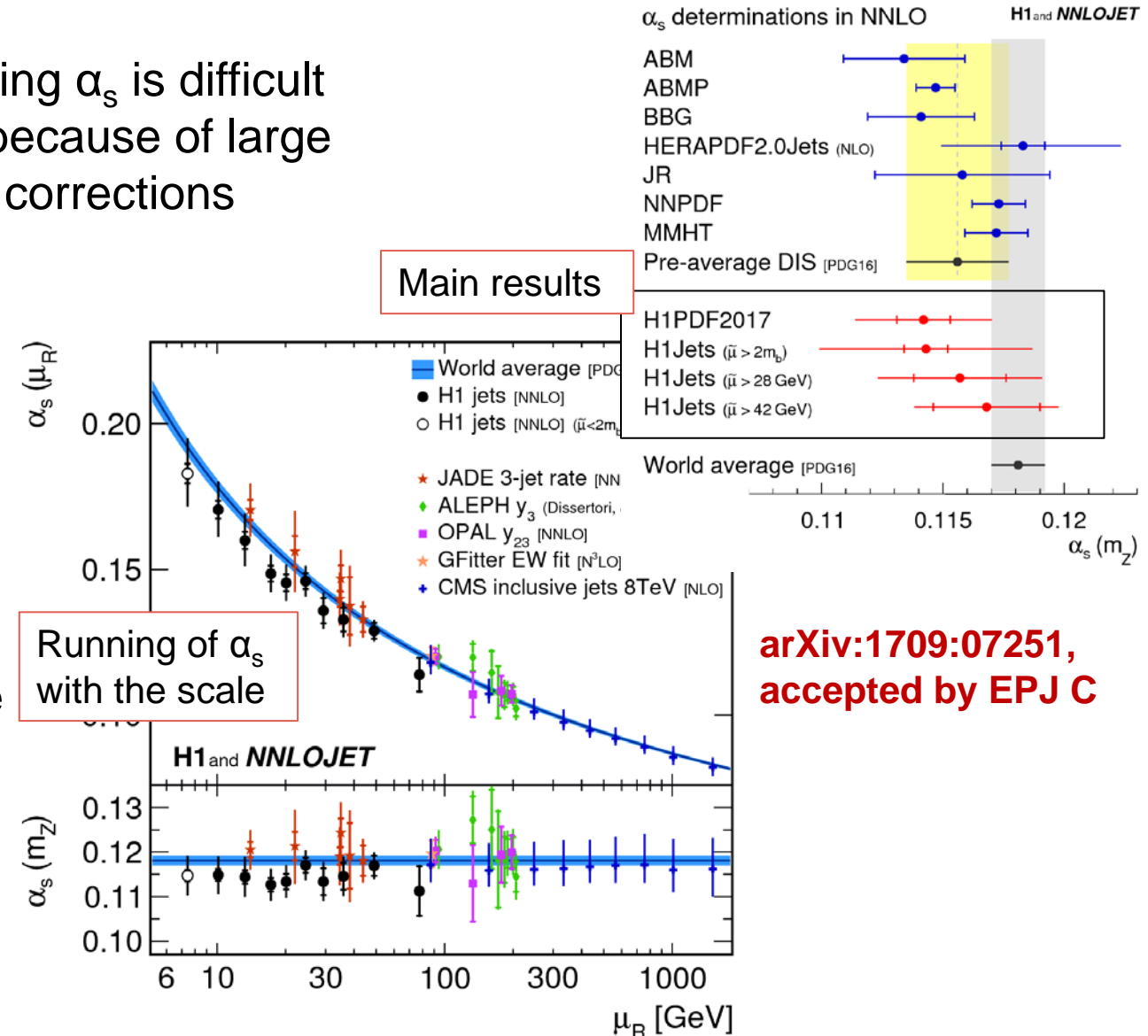
# Jet production and determination of $\alpha_s$ at NNLO

A joint effort of theorists and experimentalists



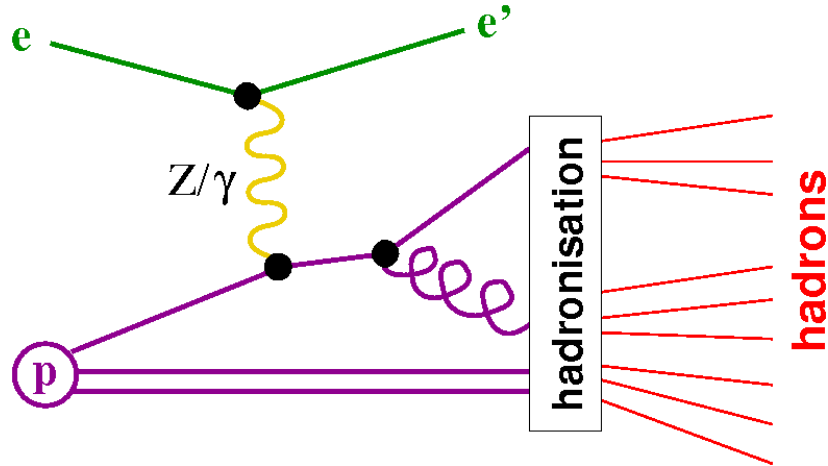
- Strong coupling  $\alpha_s$  is difficult to measure because of large higher-order corrections

- New measurement from H1 jets in next-to-next-to leading order
- First-time NNLO extraction from jet data at a hadron collider (calculations became available only in 2016)
- Close cooperation with theorists was essential
- A milestone for QCD at hadron colliders



# Identified charged pions and kaons in the proton

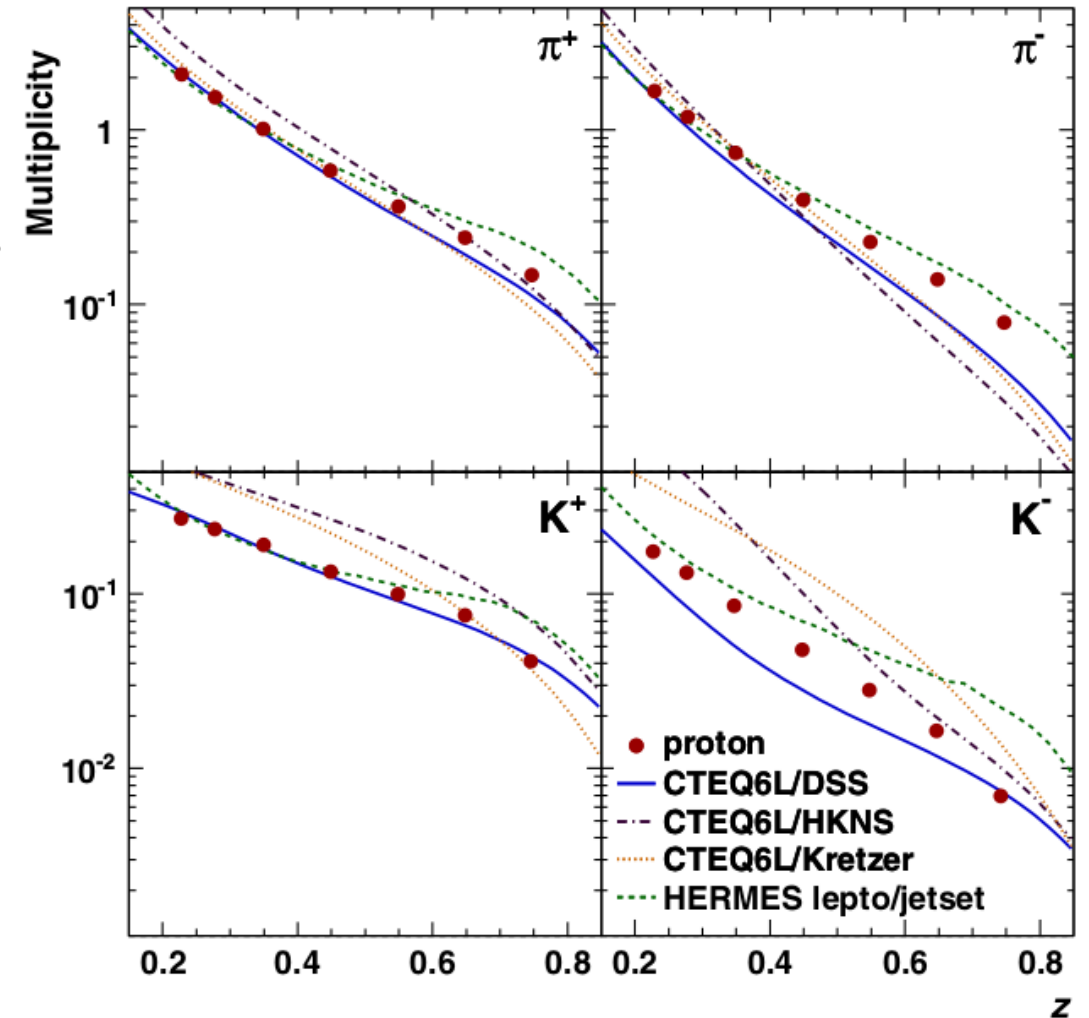
High precision measurement of the hadronisation process at low scales



$z$ : fractional hadron energy

Fragmentation functions  $f(z)$  are expected to be universal  $e^+e^-$ ,  $ep$ ,  $pp$ ,...

- HERMES: excellent particle identification
- Models fail to describe the high-precision data
- A benchmark for model builders and for improving Monte Carlo simulations
- High relevance for quark-flavor tagging via final state hadrons, e.g. in polarized scattering
- Over 100 citations in 4 years

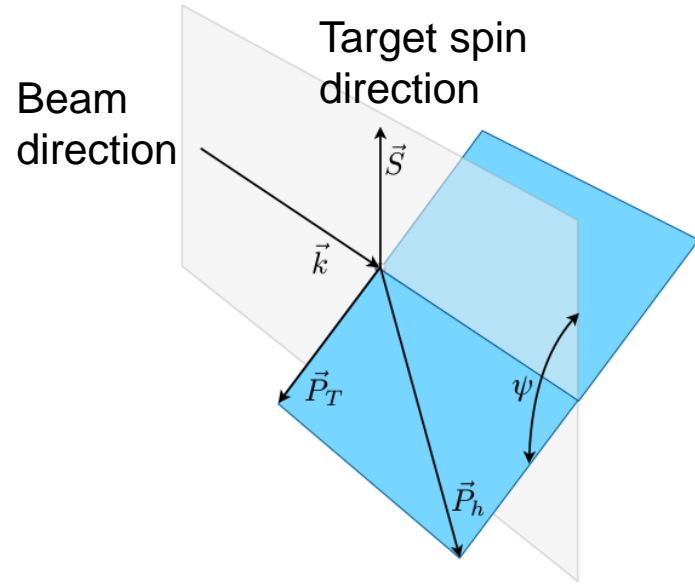


Phys.Rev.D87 (2013), 074029



# Left-right asymmetries in inclusive hadron production

Hadrons emitted from a transversely polarized target

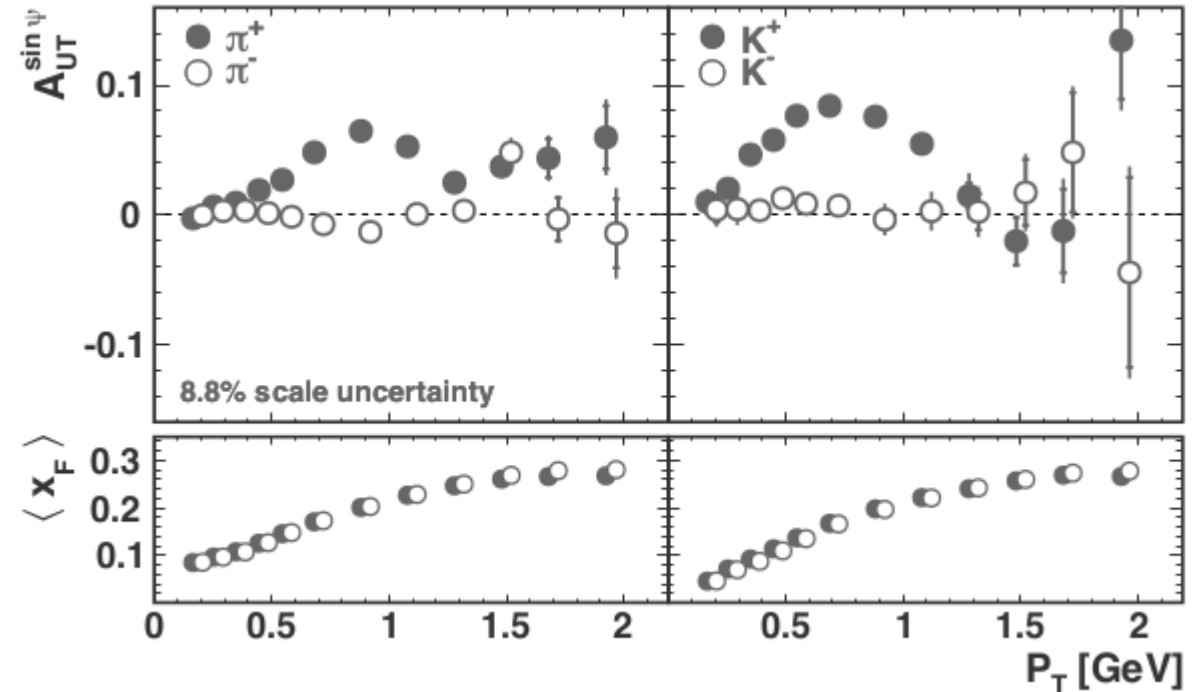


Valence quarks

p	uud
$\pi^+$	$u\bar{d}$
$\pi^-$	$\bar{u}d$
$K^+$	$u\bar{s}$
$K^-$	$\bar{u}s$

- Target spin is oriented “up” or “down”
- Electron beam is coming from the back
- Hadron asymmetry is in the left/right coordinate

$$A_{UT}^{\sin(\psi)} \sim \frac{N_L - N_R}{N_L + N_R}$$



- Sizable asymmetries for the positively charged hadrons  $\pi^+$  and  $K^+$ , much smaller for the negatively charged hadrons
- Probes spin-orbit effects of valence- and sea-quarks in the proton

# Conclusions

- POF funding for HERA ended in 2014
- The HERA data are unique: the world's only ep collider
- Data are preserved for future analysis
- Many new analyses and high-impact papers were produced years after the end of data taking
- High-precision combinations of H1 and ZEUS data are performed where possible
- HERMES continues to exploit its unique data set on polarized semi-inclusive DIS
- Stay tuned for the next +10 years after the end of HERA data taking

